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Which properties of the visual stimuli predict the type of representation used in mental rotation?

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Abstract

Two modes of internal representation, holistic and piecemeal transformation, have been reported as means to perform mental rotation (MR) tasks. The stimulus complexity effect has been proposed as an indicator to disentangle between these two representation types. However, the complexity effect has not been fully confirmed owing to the fact that different performances could result from different types of stimuli. Moreover, whether the non-mirror foils play a role in forcing participants to encode all the information from the stimuli in MR tasks is still under debate. The present study aims at testing the association between these two common types of representation with different stimuli in MR tasks. Firstly, the segments number and the vertices number in polygon stimuli were manipulated to test which property of the visual stimuli is more likely to influence the representation in MR tasks. Secondly, the role of non-mirror foils was examined by comparing the stimulus complexity effect in both with- and without-non-mirror foils conditions. The results revealed that the segments number affected the slope of the linear function relating response times to rotation angle but the vertices number in the polygons did not. This suggests that a holistic representation was more likely to be adopted in processing integrated objects, whereas a piecemeal transformation was at play in processing multi-part objects. In addition, the stimulus complexity effect was observed in the with-non-mirror foils condition but not in the without-non-mirror foils one, providing a direct evidence to support the role of non-mirror foils in MR tasks.

Key words: mental rotation; modes of representation; stimulus complexity; non-mirror foils

Introduction

The ability to form and manipulate the representation of an object in one's mind is crucial to learning, reasoning and language comprehension (Amit & Greene, 2012; Dils & Boroditsky, 2010). Mental rotation (MR) tasks typically assess this ability (Shepard & Metzler, 1971; Just & Carpenter, 1985). Individual differences in MR have been accounted for in terms of age (Dror, Schmitz- Williams & Smith, 2005), gender (Heil & Jansen-Osmann, 2008), spatial skills (Khooshabeh, Hegarty& Shipley, 2013) as well as vividness of visual imagery (Zhao & Della Sala, 2018) in behavioural (Dror et al., 2005; Khooshabeh et al., 2013; Zhao & Della Sala, 2018), neuroimaging (Logie, Pernet, Buonocore, & Della Sala, 2011) and patients studies (Zeman, Della Sala, Torrens, Gountouna, McGonigle, & Logie, 2010). The possibility has been proposed that these differences are due to the different modes of the internal representation to comply with the requirements of MR tasks (Logie et al., 2011; Zeman et al., 2010: Zhao & Della Sala, 2018).

Two typical types of representations were suggested: holistic and piecemeal. The holistic mode is assumed to rely on depictive representations which are rotated as a whole in one's mind's eye, akin to the actual physical rotation (Cooper & Shepard, 1984; Metzler & Shepard, 1974). Piecemeal transformation, on the other hand, refers to the discrete manipulations of the information stored rotated piece-by-piece in one's mind (Just & Carpenter, 1976; Yuille & Steiger, 1982). The format of the representation could be either depictive or symbols/propositions (Bethell-Fox & Shepard, 1988). By using either mode, the response times (RTs) in MR tasks linearly increase with the increase of the angular disparity (Cooper & Shepard, 1984; Kosslyn, 1981; Shepard & Metzler, 1971).

The effect of the stimulus complexity has been indicated as a means to distinguish between these two types of internal representations (Dror et al., 2005; Heil et al., 2008; Khooshabeh et al., 2013; Zhao & Della Sala, 2018). When using the holistic mode, the internal depictive representation is maintained and manipulated as a whole, hence response times (RTs) should linearly increase with angular disparity only. On the other hand, in piecemeal transformation, more time is needed to transform the symbols or propositions of objects of higher complexity during MR processing. Therefore, RTs should not only depend on angular disparity, but also on the complexity of the representation. Accordingly, a steeper slope would occur in the function relating RTs to angular disparity, which was suggested to reflect the rate of mental rotation (MR rate) whereas the intercept would reflect all the other non-rotation sub-processes including stimuli encoding or response making (Cooper & Shepard, 1973; Just & Carpenter, 1976, 1985).

In early work investigating this stimulus complexity hypothesis (Cooper, 1975), participants were instructed to respond to rotated polygons and to discriminate whether they are identical or in mirrored version. The complexity of the polygons was manipulated by changing the number of their vertices (following Attneave & Arnoult, 1956). No effect of complexity was found in these early studies (Cooper, 1975; Cooper & Podgorny, 1976), suggesting the view that the holistic mode was at play. However, in subsequent studies with polygon stimuli (Folk & Luce, 1987) as well as in other studies using arm-like cubes as stimuli (Bethell-Fox & Shepard, 1988; Yuille & Steiger, 1982), the effect of stimulus complexity was observed, supporting the piecemeal transformation account.

This failure to find the complexity effect may have resulted from the fact that the required discrimination was always between a standard object and its mirrored image. Participants can carry out such discrimination based on a small set of information from the visual stimuli, regardless of the complexity of the stimuli (Liesefeld & Zimmer, 2013). The possibility that the representation of visual stimuli could be simplified regardless of the complexity of the stimuli was supported by behavioural and ERP experiments (Yuille & Steiger, 1982; Liesefeld & Zimmer, 2013). Liesefeld and Zimmer (2013) assessed participants with *simple*, *visually complex* (with additional rotation-independent information) and *complex* (with additional rotation-dependent information) stimuli. They found that the *visually complex* objects could be rotated as efficiently as the *simple* ones and showed a much steeper slope than the *complex* stimuli.

To avoid the generation of this simplified representation, Cooper and Podgorny (1976) introduced an experimental manipulation whereby participants had to discriminate the canonical stimulus not only from its mirror version, but also from a set of non-mirror foils, which varied in their similarity to the target objects. It is assumed that in this situation participants have to encode all the information of the visual stimuli to successfully comply with the task. Whether the application of the non-mirror foils could successfully force participants to encode all the information in the visual stimuli is still unclear. Inconsistent results regarding this complexity effect were still reported in the experiments where participants have to discriminate not only between canonical and mirror version, but also between standard and non-mirror foils (Cooper & Podgorny, 1976; Folk & Luce, 1987). Anderson (1978) suggested that even with non-mirror foils, when processing a complex object (i.e., polygons with twenty vertices) where too much information needs to be encoded, participants may fail to do so and instead generate a simplified representation of the stimuli. Folk and Luce (1987) manipulated the similarity of the non-mirror foils and found that the stimulus complexity effect was only reliable with highly similar non-mirror foils, but not those with low similarity. These results provided a possible explanation for the inconsistent results.

However, it is worth noting that the stimulus similarity in Folk and Luce's (1987) experiment was based on the participants' subjective rating when they were asked to rate the similarity between the canonical and its non-mirror foils at upright position. Another group of participants' MR performances were analysed with these pre-defined stimuli. The perceived similarity for the stimuli may vary from individual to individual and therefore may decrease the reliability of the pre-defined stimulus similarity. In addition, the stimulus complexity was only manipulated by changing the number of vertices (only 6- and 10-vertice polygons were used) of integrated polygons (see the following paragraph where the complexity could be manipulated by changing the number of perceptual distinct pieces). Whether and how the non-mirror foils work in MR with non-integrated stimuli is still unknown.

Alternatively, the observed inconsistent results could be accounted for by the difference in how the stimulus complexity is manipulated. Two variables are commonly adopted in the literature: 1) the number of components of an integrated object, such as the number of its vertices (e.g., polygons, Cooper & Podgorny, 1976 and Folk & Luce, 1987) or the number of squares in a matrix (e.g., Bethell-Fox & Shepard, 1988); and 2) the number of perceptually distinct pieces, such as the figure patterns in a matrix (Bethell-Fox & Shepard, 1988) or the number of segments in 3-D blocks (e.g., Yuille & Steiger, 1982). Bethell-Fox and Shepard (1988; see also Podgorny & Shepard, 1983) found that the number of distinct pieces correlated with RTs in MR. Accordingly, piecemeal transformation was suggested to be more likely to operate in multi-part objects (Yuille & Steiger, 1982; Shepard & Feng, 1972). However, to our knowledge, no study directly investigated the relationship between the properties of the stimuli and the mode of the internal representation in MR tasks.

Therefore, the aim of the present study was to investigate which properties of visual stimuli predict the mode of representation in MR tasks. Polygons of increasing complexity were selected as the stimuli for this experiment, as they were used in Cooper's experiments (1976; Cooper & Podgorny, 1976) and in a series of ensuing studies investigating the complexity effect (e.g., Folk & Luce, 1987) to address two research questions. *Firstly*, which type of stimulus complexity manipulation is more likely to disentangle these two hypotheses, the number of vertices or the number of segments? A subset of six types of stimuli were selected with three different levels of the number of vertices (six, nine and twelve) and two levels of the number of segments (integrated vs. two-part; see top six rows in Fig. 1).

We predicted that the integrated objects could be stored and transformed as a whole as posited by Cooper (1975; and Cooper & Podgorny, 1976) whereas participants would find it difficult to represent the multi-part objects as whole, hence transforming them piece-by-piece in their minds' eyes. As such, there would be a main effect of the number of segments and a steeper slope would show in the two-segment polygons, rather than in the integrated ones, but with no main effect of the number of vertices.

Secondly, the influence of non-mirror foils in the representation mode in MR tasks was addressed. Two conditions were introduced, with- and without-non-mirror foils, to test the role of non-mirror foils in MR directly. If the non-mirror foils have indeed the ability to force participants to encode all the information of the visual stimuli, there would be an effect of non-mirror foils. In addition, stimulus complexity effect would be found under with-non-mirror foils condition but not in the without-non-mirror foils session.

Method

Participants

Twenty-two participants (mean age = 21.5, range: 19 to 24 years old, ten women) were recruited for this experiment. All were students at University of Edinburgh who received study credits for their participation. All participants were right handed, with no history of neurological disorders and reported having normal or corrected-to-normal vision.

Stimuli

The stimuli were presented in white on a black background. They were 5.5 cm in height subtending 4.55° of visual angle. As shown in Fig.1, there were 12 experimental conditions in the current experiment with three variables being manipulated: 1) number of vertices; 2) number of segments and 3) with- or without-non-mirror foils. Two subsets of stimuli were selected separately to address the two sets of research questions.

----- Insert Figure 1 about here -----

A self-written Matlab program was used to generate the eight types of canonical stimuli (see top eight rows in Fig.1). As pointed out by Anderson (1978), partial image or small portion of information could be remembered in processing the more complicated polygon with too many vertices. To avoid this, in the present paper, we selected the vertices number from the small number range from 6 to 12. A set of random non-sense integrated polygon stimuli (see the leftmost column in the first three rows in Fig.1) was generated. The shapes of these integrated polygons varied in the number of vertices, determining the inflection of the perimeter, a measure highly correlated with the rating of perceptual complexity of such forms (Attneave, 1957). This manipulation of the stimuli complexity was used in previous studies (Cooper, 1975; Cooper, & Podgorny, 1976; Folk, & Luce, 1987) following Attneave and Aroult's (1956) Method I. In the present study, the more complex stimuli were generated by adding three more vertices randomly on the simpler integrated polygon stimulus. In such a way, the original positions of the vertices in the simple polygon did not change.

A set of multi-part polygon stimuli (see the leftmost column in row 4 to 8 in Fig.1) was generated by dividing the corresponding integrated object in two, three or four segments but kept the positions of the vertices in the prototype. In this case, as can be seen in the leftmost column in row 4-6 in Fig.1, the configuration and position of the small triangle was kept exactly the same in all the three types of the two-segment polygon stimuli. The complexity of these canonical multi-part stimuli was manipulated by changing the complexity (manipulated by the vertices number) of one segment involved only. In addition, the location of the vertices was exactly the same for those with the same vertices number (e.g., see the first and forth row in Fig.1).

A set of *non-mirror foils* were generated (columns 4 to 7 in Fig.1), as in previous studies (Cooper, 1975; Cooper & Podgorny, 1976), for each canonical stimulus (the first column in Fig.1). A Matlab program was written to randomly perturb the coordinates of any point of the canonical stimuli with the amplitude ranged from 0.1 to 0.5. For each of the ten canonical polygon objects, 30 different permutations were generated and four were selected for testing based on the following two criteria: 1) all segments/vertices in the stimuli were manipulated: a. in the integrated Six-vertices, Nine-vertices and Twelve-vertices polygons, four non-consecutive vertices were perturbed; b. in multi-part objects, at least one vertex was manipulated in each segment; 2) the similarity between the non-mirror foils and the canonical stimuli modulates the stimulus complexity effect (Folk & Luce, 1987); to avoid such effect, the similarity of the four selected non-mirror foils was counterbalanced by choosing two high- and two low-similarity perturbations. Their similarity was determined by the amplitude being perturbed and controlled for. The average perturbed amplitude is 0.27, and the similarity across the ten types of stimuli were roughly equal ($SE = .01$).

To investigate the question on which property of visual stimuli predicts the representation mode in MR tasks, a subset of stimuli (see the first six rows in Fig.1) was selected varying with vertices number (six, nine and twelve; six, nine and twelve) and the *segment number* (one or two). Another subset of the stimuli was selected to address the question about the role of non-mirror foils in MR performance, with twelve vertices were selected (see the third row and row 6 to 12 in Fig.1) in with- and without-non-mirror foils conditions separately. Notably, the location and the number of the vertices in all these canonical stimuli was exactly the same. The stimulus complexity was only manipulated by changing the segment number (one, two, three and four).

For each stimulus type, a pair of objects was presented on the screen with three angular disparity (0°, 60° and 120°) either clockwise or counter clockwise (two orientations of rotation). In with-non-mirror foils condition, as summarized in the first eight rows in Fig.1, three categories of paired stimuli were presented with a different orientation: 1) one object paired with an identical object; 2) one object with its mirrored object or 3) one object with one of its corresponding non-mirror foils. Identical pairs were presented on five instances whereas both the mirrored and four foils were presented only once (see Fig.2). In without-non-mirror foils condition as shown in the four bottom rows in Fig.1, two types of pairs were presented. In half of the trials one object was paired with an identical object in a different orientation, whereas in the other half its mirrored figure was presented still in a different orientation. Both identical and mirrored pairs were presented five times (see Fig.2). For each combination as depicted in the leftmost column of Fig.1, 60 trails were randomly presented in one block. All considered, 720 trials were included in this twelve-block experiment including eight blocks with non-mirror foils and the other four without non-mirror foils.

Procedure

Participants were required to sit in front of a computer with the keyboard all masked except for two buttons marked "S" and "D", indicating "same" and "different" respectively. For half of the participants, the "S" button was set on their right hand side and the "D" button on their left side. For the other half of the participants, the "S" button was set on their left side and the "D" on their right. During the whole procedure, the participants were asked to keep their hands on the keyboard.

For each trial (see Fig. 2), first a black screen was presented for 250ms, followed by a fixation cross lasting 200ms to 250ms then a pair of polygons were presented for 4,000ms or until participants responded. Participants were instructed to indicate whether these two objects were the same (*identical* though rotated) or different (*mirrored* or *non-mirror foils* pairs in the with-non-mirror foils condition or *mirrored* pairs in without-non-mirror foils condition) by pressing the "S" or "D" button respectively.

The blocks were presented in random order for with- and without-non-mirror foils sessions. The order of the two sessions were counterbalanced across participants. Before each session, a run-in of 15 trials served as a practice allowing participants to familiarize with the task. The polygon stimuli as well as the non-mirror foils were different from the ones used in the real experiment.

----- Insert Figure 2 about here -----

Data analysis

Prior to the analysis, RTs data were trimmed for outliers. RTs that were more than two standard deviations above or below their mean value per condition and per participant were excluded (12.6% of the data on average). The results were analysed based on the identical trials only[1]. Gender was not included as a factor for data analysis[2]. Two subsets of stimuli were selected for data analysis to address the two questions set for the present study separately as summarized below.

To investigate the *first* question on which properties of the visual stimuli are more likely to predict the type of the internal representation in MR, two variables were firstly taken into account, namely *vertices number* and *segment number*. Six types of stimuli in the session with non-mirror foils (see top six rows in Fig.1) were considered[3]. A repeated-measures analysis of variance (ANOVA) was applied to the accuracy rate and the corrected RTs with three within-subject factors: three levels of *vertices number* (six, nine and twelve), two levels of *segment number* (one and two) and three levels of *angular disparity* (0°, 60° and 120°). Trend analysis would be applied in each condition followed by Bonferroni corrected pairwise comparisons, once the main effect of angular disparity or vertices number was observed. We fitted a linear line to each participant's RTs in each experimental condition to calculate the slope and intercept of this line. A repeated-measures ANOVA was used to analyse the estimated slope and intercept measurements with *vertices number* and *segment number* as two within-subject factors. Whenever appropriate, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity.

To investigate the *second* question on whether and how non-mirror foils affect the type of the internal representation in MR, an additional factor, non-mirror foil, was introduced in the analysis to directly compare the MR performance in with- and without-foils condition. The stimulus complexity was only manipulated by the number of segments. Therefore, the data of

[1] It is typical to analyze the identical trials only (e.g. Metzler & Shepard, 1974) as differential neural mechanisms were suggested to underline identical and mismatched trials (Martinaud et al., 2016) and RTs for mismatched trials are harder to interpret because the rotation angle is not well defined.

[2] We ran the analysis of covariance (ANCOVA) with gender as a co-variate and found gender did not interact with all other factors, all p-values $\geq .045$. Therefore, gender was excluded from the analyses reported in the present paper.

[3] It is impossible to involve three or four segments in the six- or nine-vertices polygons according to our design. Therefore, the stimuli with one or two segments were analysed for the first question.

four types of twelve-vertices polygon varies with their segment number in with- and without-non-mirror foils condition (the bottom eight rows in Fig.1) was selected for analysis. A repeated-measures ANOVA was applied to accuracy and corrected RTs with three within-subject factors: *segment number* (one, two, three and four), *angular disparity* (0°, 60° and 120°) and two levels of non-mirror *foils* (with and without). Once the main effect of angular disparity was found, linear trend analysis would apply followed by Bonferroni corrected pairwise comparisons. We then fitted a linear line to each participant's RTs in each experimental condition to calculate the slope and intercept of this line. A repeated-measures ANOVA method was used to analysis the estimated slope and intercept measurements with two within-subject factors: *segment number* (one, two, three and four) and *non-mirror foils* (with vs. without). Once segment number was found to affect either the slope or the intercept or to interact with the non-mirror foil, linear trend analyses would apply in each experimental condition to test the effect of segment number.

Results

Results are reported in two parts below to address the two research questions separately.

Vertices number vs. segments number

Accuracy

A main effect of *segment number* was observed in the accuracy rates, F (1, 21) = 8.35, p = .009, η_p^2 = .28. The accuracy rate in processing the two-segment objects (mean = 81.3%, SE = 2.4) was significantly poorer than that in processing the integrated objects (mean = 86.9%, SE = 2.1). A main effect of *vertices number* was also found, F (2, 42) = 9.43, $p <$ .001, η_p^2 = .31. Trend analysis confirmed that the accuracy rate linearly increased with the increasing vertices number, F (1, 21) = 21.87, $p <$ .001, η_p^2 = .51. Post-hoc analysis with Bonferroni correction revealed that the accuracy rate in processing six-point polygons (mean = 78.7%, SE = 2.1) was significantly poorer than that in processing both nine-point (mean =86.7%, SE = 2.8), p = .008, and twelve-point polygons (mean = 87.0%, SE = 1.8), $p <$ .001.

Consistent with previous literature, a main effect of *angular disparity* was observed, F (2, 42) = 42.41, $p <$ .001, η_p^2 = .67. Confirmed by linear trend, the linearly decrement was observed in accuracy rates with the increasing angular disparity, F (1, 21) = 13.94, p = .001, η_p^2 = .40. The Bonferroni-corrected planned comparison showed that accuracy rate in processing the polygons in the up-right position (0°; mean = 95.6 %, SE = 1.8) was significantly greater than that in processing the 60° rotated stimuli (mean = 80.0%, SE = 2.5), $p <$ .001, as well as the 120° rotated ones (mean = 76.7%, SE = 2.8), $p <$ .001. No interaction was observed in the accuracy rate (*segment number* × *angular disparity*: F (2, 42) = 1.52, p = .231; *vertices number* × *angular disparity*: F (4, 84) = 2.07, p = .093, η_p^2 = .09; *segment number* × *vertices number* × *angular disparity*: F (4, 84) = 2.29, p = .066), η_p^2 = .10.

Response times

RTs data are summarized in the left panel of Fig. 3. As expected, significant longer RTs were observed in processing two-segment polygons (mean = 1938.9ms, SE = 79.3) compared to the integrated ones (mean = 1609.6ms, SE = 87.4; see Fig. 4), F (1, 20) = 57.07, $p < .001$, $\eta_p^2 = .74$. However, no main effect of *vertices number* was found, F (2, 40) = .80, $p = .073$, $\eta_p^2 = .04$.

A main effect of *angular disparity* was found in RTs, F (2, 42) = 154.51, $p < .001$, $\eta_p^2 = .89$. As reported in the previous literature, the RTs increased with the increasing angular disparity in a linear trend, F (1, 20) = 219.21, $p < .001$, $\eta_p^2 = .92$. Revealed by post-hoc analyses with Bonferroni correction, significantly longer RTs were observed in processing the stimuli at 120° (mean = 2088.5ms, SE = 90.6) compared to those in smaller rotation angle (0°, $p < .001$; 60°, $p < .001$); RTs in processing the stimuli at 60° (mean = 1948.2ms, SE = 95.2) was observed significantly longer than that in the upright position (0°; mean = 1286.0ms, SE = 67.6), $p < .001$.

----- Insert Figure 3 about here -----

Slopes

A main effect of *segment number* was observed in the estimated slope measure, F (1, 21) = 7.01, p = .015, $\eta p^2 = .25$. As shown in Fig.3, the top right panel, a steeper slope was observed in RTs when processing the two-segment polygons (mean = 7.9ms/degree, SE = 0.6) compared to that in processing the integrated ones (mean = 6.4ms/degree, SE = 0.5).

However, no main effect of *vertices number* was found in this estimated slope measure, F (2, 42) = .44, $p = .65$, $\eta_p^2 =.02$. Furthermore, there was no *vertices number* × *segment number* interaction, F (2, 42) = .76, $p = .48$, $\eta_p^2 =.03$.

Intercepts

Intercepts are depicted in the bottom right of Fig.3. A main effect of *segment number* was found in the estimated intercept, F (1, 21) = 34.14, $p < .011$, $\eta_p^2 = .62$. Longer times were needed in encoding the stimuli or in giving response in two-segment polygons (mean = 1490.3ms, SE = 69.6) than those in integrated ones (mean = 1249.6ms, SE = 72.8). No main effect of *vertices number* was observed in the intercept measure, F (2, 42) = 2.23, $p = .120$, $\eta_p^2 = .10$.

However, *vertices number* was found to interact with *segment number* in the intercept measure, F (2, 42) = 13.58, $p < .001$, $\eta_p^2 = .39$. A repeated-measures ANOVA method was applied to the integrated polygons (segment number = 1) and two-segment polygons (segment number = 2) separately. In processing the integrated polygon stimuli, there was a main effect of vertices number in the intercept, F (2, 42) = 11.90, $p < .001$, $\eta_p^2 = .36$. Confirmed by the trend analysis that the intercept linearly increases with the vertices number in the polygon stimuli, F (1, 21) = 18.61, $p < .001$, $\eta_p^2 = .47$. Post-hoc analyses with Bonferroni correction revealed that significantly longer time was spent in either stimuli encoding or giving responses with the polygons with twelve vertices (row five in Fig.1; mean = 1443.2ms, SE = 110.5) than in the polygons with nine vertices (row three in Fig.1; mean = 1224.1ms, SE = 69.8), $p = .015$, or with six vertices (row one in Fig1; mean = 1081.6ms, SE = 66.3), $p < .001$. On the other hand, in processing the two-segment polygons, no vertices number effect was found, F (2, 42) = 1.64, $p = .206$, $\eta_p^2 = .07$, suggesting that the vertices number did not affect the sub-phase in either stimuli encoding or giving responses in two-segment polygon stimuli, in which piecemeal transformation was likely at play.

The effect of non-mirror foils in MR performance

Accuracy

A main effect of *segment number* was observed on the accuracy rates, F (3, 63) = 13.83, $p < .001$, $\eta_p^2 = .40$. This was confirmed by trend analysis showing that the accuracy rates linearly decreased with the increasing segment number, F (1, 21) = 29.41, $p < .001$, η_p^2

= .58. Post-hoc analysis with Bonferroni correction further revealed that the accuracy rate in processing the two-segment polygon (mean = 87.5%, SE = 2.0) remains similar to that in the integrated polygon (mean = 87.7% , SE = 2.2). However, the accuracy dropped dramatically, from the average accuracy at 87.7% $\pm$ 2.2 in two-segment polygons to that at 82.7% $\pm$ 2.8 in three-segment polygons, p = .003, and at 77.8% $\pm$ 2.9 in four-segment polygons, $p < .001$. However, no main effect of non-mirror *foils* was found, F (1, 21) = 2.41, p = .135, η_p^2 =.10.

Consistent with previous literature, a main effect of *angular disparity* was found in the accuracy, F (2, 42) = 49.07, $p < .001$, η_p^2 = .70. As indicated by trend analysis, the accuracy decreased linearly with the increasing segment number, F (1, 21) = 64.67, $p < .001$, η_p^2 = .76. Post-hoc analysis with Bonferroni correction revealed that the accuracy dropped from 95.1% $\pm$ 1.8 at up-right position (0°) to 81.7% $\pm$ 2.7 at 60°, $p < .001$, and continued drop till 75.0% $\pm$ 3.0 at 120°, p = .006.

While no other interaction found in the accuracy rate (*non-mirror foils* × *segment number*: F (2.192, 46.039) = .232, p = .813, η_p^2 = .011; *non-mirror foils* × *angular disparity*: F (2, 42) = 0.92, p = .407, η_p^2 = .04; *non-mirror foils* × *segment number* × *angular disparity*: F (6, 126) = 1.29, p = .268, η_p^2 = .06), the interaction of *segment number* and *angular disparity* was detected, F (6, 126) = 2.06, p = .021, η_p^2 = .11. By analysing the estimated slopes and intercepts in the accuracy rate, we found the following results with regard to the *segment number* × *angular disparity* interaction: there was no effect of segment number found on the intercept in the accuracy rates, F (2.0, 43.9) = 1.94, p = .132, η_p^2 = .08; however, such segment number effect was found in the slope measure, F (2.0, 43.2) = 4.96, p = .012, η_p^2 = .18, which fitted with a linear trend, F (1, 22) = 7.45, p = .012, η_p^2 = .25.

Response times

The RTs under different stimuli types are reported in the left panel in Fig. 4. *Segments number* of the stimuli affected the RTs in MR tasks, F (3, 63) = 21.27, $p < .001$, η_p^2 = .50.

Trend analysis further indicated that the RTs were linearly increased with the increasing segment number, F (1, 21) = 37.84, $p < .001$, $\eta_p^2 = .64$. Significant longer RTs were observed in processing the stimuli with three segments (mean = 1995.2ms, SE = 75.1) comparing to the integrated ones (mean = 1749.4ms, SE = 74.8), $p = .009$, as well as those consisted of two segments (mean = 1670.3ms, SE = 69.9), both ps ≤ .001. In addition, longer RTs were observed in processing the four-segment polygons (mean = 2182.8ms, SE = 89.2) than in the ones with three segments, $p = .043$. A main effect of *non-mirror foils* was also found in the RTs, F (1, 21) = 16.63, $p = .001$, $\eta_p^2 = .44$. As expected, significant longer RTs were required in with-non-mirror foils condition (mean = 2075.6ms, SE = 92.3) than in the without-non-mirror foils one (mean = 1723.3ms, SE = 58.2).

As reported in previous literature, there was a main effect of *angular disparity* in the RTs, F (2, 42) = 336.26, $p < .001$, $\eta_p^2 = .94$. As verified by trend analysis, RTs were linearly increased with the increasing angular disparity, F (1, 21) = 624.24, $p < .001$, $\eta_p^2 = .97$. RTs in processing the stimuli at 60° (mean = 2034.2ms, SE = 75.4) were significantly longer than in processing those in the upright position (at 0°; mean = 1358.6ms, SE = 66.5), $p < .001$. Significantly longer RTs were observed in processing the stimuli at 120° position (mean = 2305.6ms, SE = 59.7) than those rotated at 60°, $p < .001$.

----- Insert Figure 4 about here -----

Slopes

A main effect of *segment number* was observed in the slope measure, F (3, 63) = 5.34, $p = .002$, $\eta_p^2 = .20$. Slower MR rate was observed in processing the stimuli with more segments. Trend analysis further indicated that the MR rate became linearly slower with the increasing number of segments, F (1, 21) = 162.17, $p = .001$, $\eta_p^2 = .43$. The MR rate in processing the four-segment polygons (mean = 8.9ms/degree, SE = 0.6) was significantly slower than that in processing the integrated ones (mean = 6.5ms/degree, SE = 0.4), $p = .012$.

In addition, there was a main effect of *non-mirror foils* on the slope measure in the RTs function of angular disparity, $F\,(1, 21) = 34.10$, $p < .001$, $\eta_p^2 = .62$. In the without-non-mirror foils condition (mean = 6.6ms/degree, SE = 0.3), participants performed much faster as compared to their performance in the with-non-mirror foils condition (mean = 9.0ms/degree, SE = 0.4).

The interaction of *non-mirror foils* and *segment number* was also found in this estimated slope measure, $F\,(3, 63) = 3.31$, $p = .026$, $\eta_p^2 = .14$. Repeated-measures ANOVA method was applied on the slope measure in with- and without-non-mirror foils condition separately. As depicted in the top right panel in Fig.4, the effect of segment number was evident on the slope measure in with-non-mirror foils condition, $F\,(3, 63) = 5.91$, $p = .001$, $\eta_p^2 = .22$. Trend analysis further indicated that the MR rate linearly decreased with the segment number, $F\,(1, 21) = 19.25$, $p < .001$, $\eta_p^2 = .48$. The MR rate in processing either the three-segment (mean = 10.7ms/degree, SE = 0.9) or four-segment polygons (mean = 10.6ms/degree, SE = 1.0) was significantly slower than that in processing the integrated ones (mean = 6.7ms/degree, SE = 0.6), both $p \leq .008$. On the other hand, in the without-non-mirror foils condition (see the bottom panel in Fig. 8), no effect of segment number was observed, $F\,(3, 63) = .575$, $p = .634$, $\eta_p^2 = .027$, suggesting that the holistic mode was applied in this condition.

Intercepts

A main effect of *segment number* was found in the estimated intercept measure in the RTs function of angular disparity, $F\,(3, 63) = 14.69$, $p < .001$, $\eta_p^2 = .41$. The time spent in either stimuli encoding or giving responses proved to increase linearly with the segment number, $F\,(1, 21) = 19.62$, $p < .001$, $\eta_p^2 = .48$. The time to process the four-segment stimuli (mean = 1646.2ms, SE = 101.2), either at encoding or in giving response, was significantly longer than the time spent in processing the two-segment stimuli (mean = 1242.0ms, SE = 63.9), $p < .001$, or the integrated polygons (mean = 1359.2ms, SE = 73.5), $p = .007$. In addition, the non-mirror foils were observed to affect the intercept, F (1, 21) = 6.03, p = .023, η_p^2 = .22. As expected, less time was required in either stimuli encoding or giving responses in the without-non-mirror foils condition (mean = 1314.5ms, SE = 59.0) than in the with-non-mirror foils condition (mean = 1537.3ms, SE = 100.3).

Discussion

In the present study, two questions were raised: 1) which properties of the objects are more likely to influence the types of the internal representation in MR tasks; and 2) would non-mirror foils play any role in the mode of representation in MR tasks? By manipulating the complexity level of the polygon stimuli, the internal representation mode is inferred by assessing the complexity effect on the slopes in RTs function of angular disparity as Cooper suggested (1995; see also Cooper & Podgorny, 1976).

To address the *first* question, the effect of the number of vertices as well as the effect of the number of segments in polygon stimuli were tested. The current finding is that the segments number rather than the vertices number has the main effect on the slope measure, which suggests that the manipulation of segment number in an object rather than the number of its vertices is more likely to influence the mode of representation in MR (Cooper, 1975; Cooper & Podgorny, 1976). This finding resonates with the outcome of the first experiment reported by Bethell-Fox and Shepard (1987; see also Podgorny & Shepard, 1983). In their study, the number of shaded squares and the non-adjacent pieces was manipulated within a 9 × 9 matrix. The number of non-adjacent pieces rather than the number of shaded squares correlated with RTs. One possible explanation suggested for such correlation is that longer RTs were required to transform each of the multi-part stimuli than to transform the integrated piece. The present study provided direct evidence for this hypothesis.

In addition, in previous studies (Bethell-Fox & Shepard, 1987; Podgorny & Shepard, 1983), stimuli were restricted to rotate by 90 or 180 degrees. One may argue that these two specific angles could be solved by alternative cognitive processes (at least by some participants; Cooper & Shepard, 1973; Liesefeld & Zimmer, 2011). For example, “flip over” is suggested as a way to process the stimuli in 180 degrees instead of MR (Murray, 1997; Just & Carpenter, 1985). Liesefeld and Zimmer (2011) provided evidence for this account that the representation is first flipped along the horizontal and then along the vertical axis to comply with the 180°-rotated images. To explore the effect of stimulus complexity on a more general type of the internal representation in MR tasks, these two specific angles were avoided in the present study and stimuli were rotated at either 60 or 120 degree instead.

In MR with *integrated* objects, no effect of vertices number was found on the estimated slope measure. According to Cooper's hypothesis (1975), this finding suggests that the depictive representation of the integrated objects was generated in one's mind and rotated as a whole. This is consistent with Cooper and Podgorny's (1976) study in which pure rotation times were analysed and found to be independent of the stimulus complexity. Folk and Luce (1987), however, combined the RTs with identical trials as well as those accompanied with non-mirror foils and found an interaction between stimuli similarity and complexity. The complexity effect was only observed when the non-mirror foils were similar to the canonical ones. It is possible that different cognitive processes are called upon to process trials with an identical object and those with a non-mirror foil. Additional time and resources may be needed for discriminating the difference between canonical stimuli and their non-mirror foils. In this context, the interaction of stimulus complexity and similarity on RTs found in Folk and Luce (1987) may not reflect the pure mental rotation process but is probably caused by the different RTs in discriminating canonical stimuli and their highly similar non-mirror foils. Detailed and specific differences would need to be detected and more time would be required for more complex objects. On the contrary, it would be easier to detect the difference between canonical stimuli and their less similar non-mirror foils; consequently, RTs would be independent of the stimulus complexity.

Furthermore, a steeper slope was found in processing the *multi-part* objects compared to that observed in processing the integrated ones. This result reveals that to process multi-part objects will slow the rotation rate. It is possible that participants mentally operate on stimuli consisting of perceptually distinct parts by considering one part at a time (Yuille & Steiger, 1982; Shepard & Feng, 1972). The specific format of such representation in this piecemeal transformation is still unclear (Pearson & Kosslyn, 2015). For example, in the two-segment polygons participants could maintain the vertices and their relative locations and then transform the image vertex-by-vertex, or they could maintain each segment as an independent representation and transform the stimulus segment-by-segment. No effect of vertices number was found in two-segment polygons, providing evidence that participants did not transform the individual vertices in their minds' eyes to comply with the tasks at least for these stimuli.

Given the current experimental design, one may argue that participants would learn and extract certain features (not necessarily the specific vertices) of the visual stimuli thanks to practice. This alternative explanation refers to Liesefeld and Zimmer's account (2013) suggesting that independently of the stimulus complexity, only one piece of orientation-dependent information per stimulus would need to be rotated in the present study. However, people might encode and rotate additional orientation-dependent information when they have not only to discriminate the canonical polygon stimuli from their mirror images, but also from various types of non-mirror foils. As shown in Fig.1, these non-mirror foils were designed by randomly changing the relative location of the vertices. Hence, several spatial features have changed, especially in those stimuli with fewer vertices. This may make it more difficult to decide which information is needed for comparison, resulting in slower rotation rates.

As to the *second* research question about the role of non-mirror foils in the mode of representation in MR, non-mirror foils in the present study affected the processing time as found by Folk and Luce (1987). Longer RTs were observed in processing the stimuli with non-mirror foils than those without-non-mirror foils. The analysis on the estimated slope indicated a faster MR rate in the without-non-mirror foils condition compared to that in the with-non-mirror foils condition. Moreover, non-mirror foils interacted with segment number on the estimated slope measure. The complexity effect emerged in the with-non-mirror foils condition but not in the without-non-mirror foils condition. This finding is consistent with the observations in the literature (Bethell-Fox & Shepard, 1988; Cooper & Podgorny, 1976; Yuille & Steiger, 1982) and provides a possible explanation for the inconsistent results.

In processing the stimuli with non-mirror foils, the stimulus complexity effect was observed. Steeper slopes were observed in processing the three- and four-segment objects than in processing integrated ones. These results, based on Cooper's complexity effect hypothesis (1975), suggested that piecemeal transformation was at play in processing these multi-part stimuli in MR tasks whereas holistic transformation was by default applied in processing integrated object. In such condition, more information has to be encoded to comply with the task, not only to discriminate between canonical polygon stimuli from mirror images, but also from the non-mirror foils. Alternatively, to cope with the more complex task with non-mirror foils, participants might be more careful to avoid errors; encoding more information of the visual stimuli would then result in a slower MR rate. It is notable that the MR rates in rotating an integrated object and that in rotating two-segment ones were comparable. These results provide evidence supporting the argument that participants could at most bind two segments of the stimuli in their mind's eyes for transformation in MR tasks (Xu & Franconeri, 2015).

By contrast, in the without-non-mirror foils condition, no effect of vertices number was observed. This suggests that in the without-non-mirror foils condition, participants may ignore the stimulus complexity and automatically simplify the task by encoding a partial image (Yuille & Steiger, 1982) or rotation-related information (Liesefeld & Zimmer, 2013) and maintain this simplified internal representation for further mental manipulation. The format of these partially transformed representations is unclear. It is possible that the image of the segment polygons were stored and transformed. Alternatively, the spatial rotation-related information could also be represented and transformed (Liesefeld & Zimmer, 2013).

These results considered together, confirmed the functional role of the non-mirror foils in MR tasks. The non-mirror foils increase the probability of participants encoding more, or even all, the information of the visual stimuli (see Cooper & Podgorny, 1976). However, in the without-non-mirror foils condition, participants have the ability to simplify their mental representations of the visual stimuli automatically for further mental transformation. This finding is in accordance with Liesefeld and Zimmer's suggestion (2013) that the amount of information being represented is not only based on the complexity of the rotated stimuli, but also on the type of comparison required. This finding could also be of practical use in future MR studies which should consider adding non-mirror foils to the experimental design.

In addition, considering also our previous findings whereby the cube numbers in Shepard and Metzler's typical arm-like objects did not affect the mode of representation in one's mind (Zhao & Della Sala, 2018), we could postulate that the manipulation of the complexity level of integrated objects is likely to change the type of the internal representation in a MR task. This provides a good reason for future MR studies to manipulate the stimulus complexity by changing the segments number rather than the vertices number, if polygons were selected as stimuli. As MR has been recently suggested not only as a measure of spatial abilities, but also as a way to use the more efficient analytical mode (Hegarty, 2018), MR tasks with multi-part objects could be used to predict success in science, technology, engineering, and mathematics (STEM) education and careers.

Although the significance levels are reliable, the relatively small sample size is another possible limitation of the current study. Future studies could also be carried out based on the current findings to explore other potential factors (i.e., gender or spatial ability) that might affect the default mode of the internal representation in MR tasks.

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Figure Captions

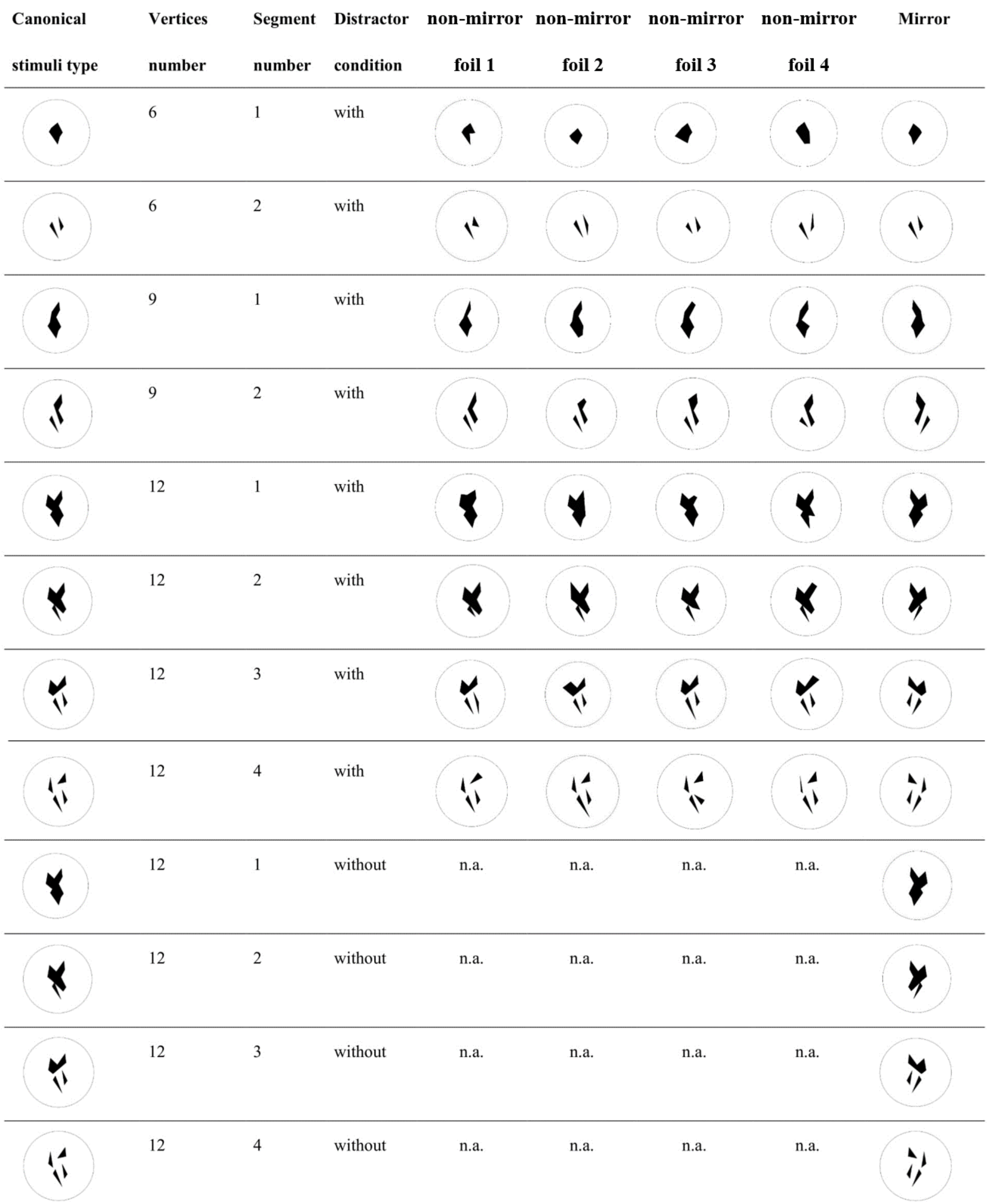
Figure 1: Twelve types of stimuli used in the experiment. To the right of each canonical type are three measures of stimulus complexity (the number of vertices, the number of segments and non-mirror foils condition) and four types of non-mirror foils and mirrored image.

Figure 2: Experimental procedure. In the with-non-mirror session (middle panel), half of the trials were a pair of identical polygon stimuli with different rotation angles with five repetitions for each pair; in the other half trials, one canonical polygon stimuli was paired with its mirrored image or four types of corresponding non-mirror foils (presented once for each type). In the without-non-mirror session (right panel), half of the trials were a canonical stimuli paired with identical stimuli with different rotation angles, the other half were paired with its mirrored image. Both types were presented in five repetitions.

Figure 3: Performance of integrated and two-segment polygon stimuli. Left panel depicts the response times across all rotation angles; top right panel presents the estimated slope whereas bottom right panel shows the estimated intercepts.

Figure 4: Performance in eight types of polygon stimuli in with- and without-non-mirror foils conditions. Left panel depicts the response times across all rotation angles; top right panel presents the estimated slope whereas bottom right panel shows the intercepts.

Figure 1



Canonical stimuli type	Vertices number	Segment number	Distractor condition	non-mirror foil 1	non-mirror foil 2	non-mirror foil 3	non-mirror foil 4	Mirror
	6	1	with					
	6	2	with					
	9	1	with					
	9	2	with					
	12	1	with					
	12	2	with					
	12	3	with					
	12	4	with					
	12	1	without	n.a.	n.a.	n.a.	n.a.	
	12	2	without	n.a.	n.a.	n.a.	n.a.	
	12	3	without	n.a.	n.a.	n.a.	n.a.	
	12	4	without	n.a.	n.a.	n.a.	n.a.	

Figure 2

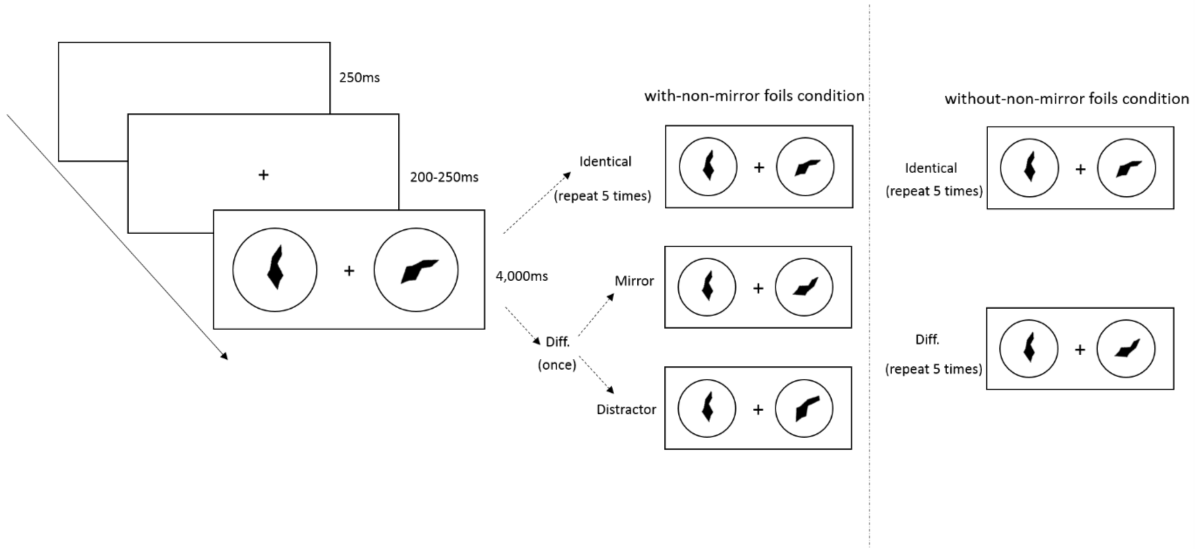

250ms
+
200-250ms
+
4,000ms
with-non-mirror foils condition
Identical
(repeat 5 times)
+
Mirror
+
Diff.
(once)
Distractor
+
without-non-mirror foils condition
Identical
(repeat 5 times)
+
Diff.
(repeat 5 times)
+

Figure 3

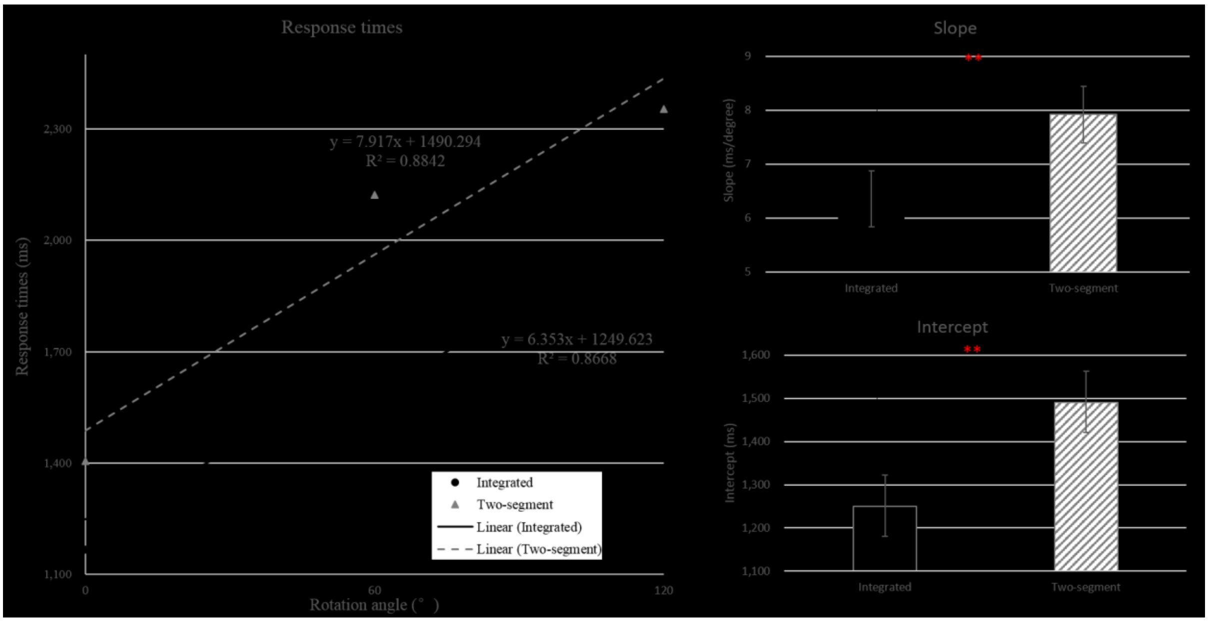
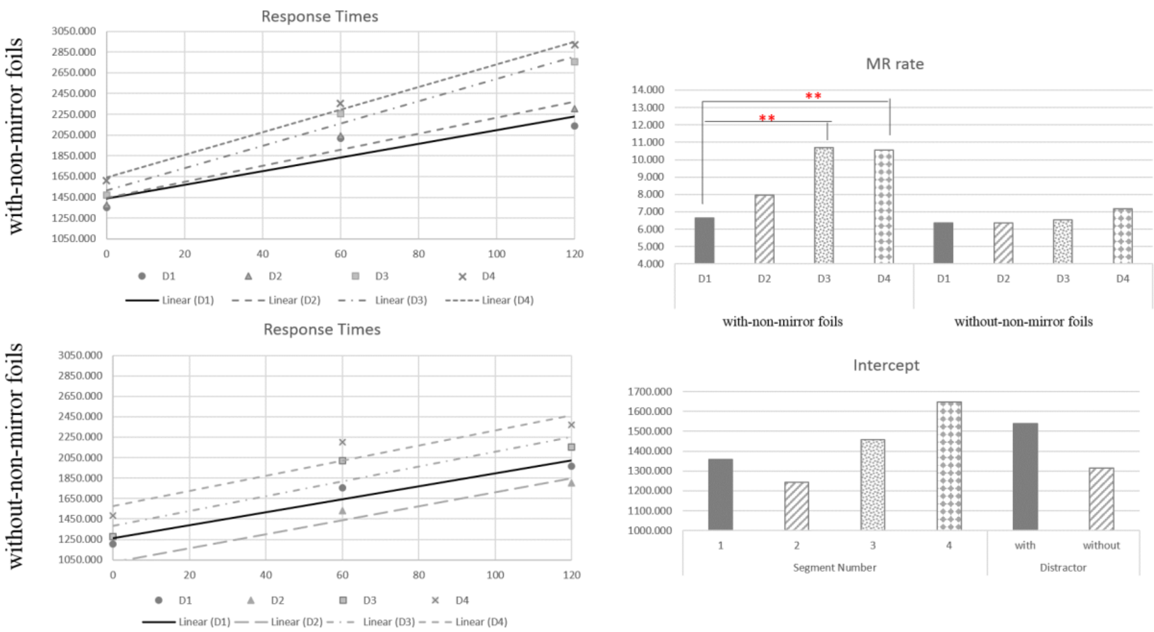

Response times
y = 7.917x + 1490.294
R² = 0.8842
y = 6.353x + 1249.623
R² = 0.8668
2,300
2,000
1,700
1,400
1,100
Response times (ms)
0
60
120
Rotation angle (°)
Integrated
Two-segment
Linear (Integrated)
Linear (Two-segment)
Slope
Slope (ms/degree)
9
8
7
6
5
**
Integrated
Two-segment
Intercept
Intercept (ms)
1,600
1,500
1,400
1,300
1,200
1,100
**
Integrated
Two-segment

Figure 4


with-non-mirror foils
Response Times
D1 D2 D3 D4
Linear (D1) Linear (D2) Linear (D3) Linear (D4)
without-non-mirror foils
Response Times
D1 D2 D3 D4
Linear (D1) Linear (D2) Linear (D3) Linear (D4)
MR rate
**
**
with-non-mirror foils
without-non-mirror foils
Intercept
Segment Number
Distractor
with
without